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FUTURE V/STOL AIRPLANES: GUIDELINES AND TECHNIQUES FOR ACQUISIT--ETC(U)

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Future V/STOL Airplanes: Guidelines and Techniques for Acquisition Program Analysis and Evaluation –Executive Summary

J. R. Nelson, J. R. Gebman

with J. L. Birkler, R. W. Hess, P. Konoske-Dey, W. H. Krase

A Report prepared for
OFFICE OF THE ASSISTANT SECRETARY
OF DEFENSE/PROGRAM ANALYSIS
AND EVALUATION

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PREFACE

The purpose of this summary report and a companion technical document* is to assist the Department of Defense in making critical evaluations of proposed vertical/short takeoff and landing (V/STOL) airplane program characteristics, including airplane performance, acquisition schedule, and acquisition cost. The guidelines and techniques described in these two documents take the form of analytical tools, data, and lessons drawn from previous V/STOL airplane research, development and acquisition experience. The documents focus exclusively on the acquisition phase for the airframe and the propulsion subsystems; avionics is not considered. The operational utility of V/STOL airplanes and the possible new missions to which V/STOL airplanes might be uniquely suited are not addressed.

This research was sponsored by the Office of the Assistant Secretary of Defense for Program Analysis and Evaluation (OSD/PA&E).

* *Future V/STOL Airplanes: Guidelines and Techniques for Acquisition Program Analysis and Evaluation*, The Rand Corporation, N-1242-PA&E, Privileged Information, October 1979.

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SUMMARY

As aeronautical technologies continue to advance, V/STOL airplanes^{*} will become increasingly more attractive for a variety of military missions.[†] The decision of whether to approve the acquisition of a V/STOL airplane for a particular mission will depend upon factors that include the airplane's expected performance capability, the likely acquisition cost, and the likely amount of time required for research and development. To develop guidelines and techniques for critically evaluating these factors, Rand has analyzed past V/STOL research and development programs, examined the current state of pertinent aeronautical technologies, and developed appropriate analytical tools where possible.

MAJOR FINDINGS

- o Without full-scale flight tests, current methods of aeronautical engineering cannot accurately estimate the performance capabilities of a V/STOL airplane.[‡]
- o An incremental strategy that includes the conduct of austere experimental programs is the most efficient approach to obtaining necessary flight-test information early in the acquisition process.
- o Advances in aeronautical technologies will improve the performance potential for future aircraft, but are not likely to lessen the problems of accurately estimating V/STOL airplane performance.

^{*} The acronym V/STOL refers to airplanes that can take off either vertically or after a short takeoff roll. The term airplane refers to fixed-wing aircraft. The acronym CTOL refers to conventional takeoff and landing airplanes. The term aircraft includes rotary-wing designs.

[†] Many of these advances in aeronautical technologies, however, will also increase the attractiveness of CTOL airplanes.

[‡] Such tests are especially important because the unknown problems that accompany the application of new technologies can bias early interest in designs that use technologies about which the least is known.

- o The acquisition of an operational V/STOL airplane will continue to cost significantly more and take significantly longer than the acquisition of a CTOL airplane that flies the same missions (except for takeoff and landing).

CONCLUSION

The introduction of future V/STOL airplanes for military missions will continue to depend on mission needs that place a high operational value on the special capabilities of V/STOL airplanes--an operational value high enough to warrant the exceptionally long development times and the premium prices (compared with CTOL airplanes) that must be paid for research, development, and procurement.

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I. INTRODUCTION

BACKGROUND

Over the past quarter of a century, aircraft companies have built and experimentally flown about two dozen different configurations of fixed-wing aircraft that take off vertically like a helicopter but cruise at significantly higher speeds and altitudes.* These experiments have explored a half dozen general concepts for accomplishing vertical takeoff. Some companies tilted the airplane (tail sitter); others tilted the propulsion system, or even the entire wing along with the propulsion system. Some companies incorporated engines that only operated during takeoff and landing; others used remote fans that only operated during takeoff and landing. Some companies explored ejector systems that entrain air that mixes with the engine's exhaust to augment the lifting forces acting on the vehicle. The Navy's recent XFV-12A program attempted such an augmentation concept. In contrast, the Marine Corps' AV-8A simply deflects the engine's exhaust gases vertically downward to accomplish vertical takeoff and landing. This airplane, developed and produced in the United Kingdom as the Harrier, remains the free world's only operational vertical/short takeoff and landing (V/STOL) airplane.†

Following a vertical takeoff with a maximum weight of about 17,000 lb, the AV-8A can carry a 1500-lb payload on a mission with a 50 n mi radius. An improved model, designated the AV-8B, has a calculated capability to fly a mission radius of 250 n mi, with the same payload. Because of this five-fold increase in radius (or alternatively an increase in payload), the Marine Corps would like to procure the AV-8B

* This report uses the term airplane to distinguish fixed-wing (including tilt wing) aircraft from rotary-wing aircraft; the term helicopter refers to rotary-wing aircraft.

† The United Kingdom uses the Harrier designation whereas the Marine Corps uses the AV-8A designation. Although the Soviet Union has also developed and deployed a V/STOL airplane, it could not be included in this study because of insufficient information.

during the 1980s. If the pilot of either the AV-8A or AV-8B has several hundred to a thousand feet of surface available, he can appreciably increase payload and/or radius by rolling the airplane along the surface for a short distance. For example, with a 1500-lb payload and a 1000-ft takeoff roll, the AV-8A has a mission radius of about 450 n mi; under the same conditions, the AV-8B has a calculated mission radius of about 850 n mi. This report refers to *fixed-wing* aircraft that can take off either vertically or with a short takeoff roll and land vertically as V/STOL *airplanes*.

MOTIVATION FOR THE RESEARCH

The improving mission performance capability of the Harrier/AV-8 airplanes has rekindled interest in more broadly applying V/STOL airplanes to military missions. For example, for the past several years the Navy has examined how it might use V/STOL airplanes to disperse its sea-based aviation forces. During 1977 the Navy advanced a plan to replace all sea-based aircraft with V/STOL airplanes, and toward the end of 1977 it appeared that the Navy was considering a major commitment to acquire such airplanes. To do so, analysis and evaluation guidelines and techniques applicable to V/STOL airplanes would be needed to evaluate the new acquisition programs. Staff elements responsible for evaluation ideally would prefer generalized techniques to assess the performance, schedule, and cost expectations for any type of V/STOL airplane. To help develop appropriate evaluation guidelines and techniques, Rand was asked to (1) examine airframe and propulsion technologies pertinent to future V/STOL airplanes; (2) develop guidelines and techniques for analyzing and evaluating performance, schedule, and cost expectations for future V/STOL airplanes; and (3) apply the guidelines and techniques to help analyze and evaluate the Navy's tentative acquisition plan.

A September 1977 article by the then Chief of Naval Operations describes an approach to replacing all sea-based aircraft with V/STOL airplanes.* Although the Navy has not proposed any specific acquisition

*Admiral James A. Holloway, III, "The Transition to V/STOL," *Proceedings of the United States Naval Institute*, Vol. 103, No. 9, September 1977, pp. 19-24.

plans, it has continued to reexamine its master plans for sea-based aviation, including V/STOL alternatives. This report focuses on the 1977 article as an example of a plan to acquire V/STOL airplanes.

The 1977 article called for three types of V/STOL airplanes to replace all sea-based airplanes and helicopters. The Type A airplane would replace nearly a dozen different types of subsonic aircraft, which have assigned missions for antisubmarine warfare, advanced early warning, carrier on-board delivery, search and rescue, and marine assault. The Type B airplane would replace about a half dozen different types of subsonic and supersonic aircraft, which have assigned missions for air-to-air combat, air-to-surface attack, and reconnaissance. Eventually, the Type C airplane would replace a half dozen types of small helicopters.

To assure an orderly replacement of current aircraft as they reach the end of their service lives, the 1977 article specified that the Type A airplane would have to have an initial operational capability (IOC) in the early 1990s, whereas the Type B airplane could have a mid-1990s IOC. The 1977 article further stated that the Navy should attempt to hold the cost to research, develop, and procure the V/STOL airplanes to those costs that the Navy would normally incur to replace conventional takeoff and landing (CTOL) airplanes and helicopters.

OVERVIEW OF THE RESEARCH

When this research started, critical questions had already been raised about the performance, schedule, and cost expectations described in the 1977 article. For example, both the Naval Air Systems Command and the aircraft industry had knowledge that the Type A and B airplanes would have to incorporate significant advances in many technologies to achieve the performance levels specified by the Navy. How far would these technologies have to advance to allow the Type A and B airplanes to satisfy the performance specifications? How long would it take and how much would it cost for the industry to provide airplanes that could meet the Type A and B performance specifications? These basic questions strongly influenced the initial direction for

this research. As work progressed, the lack of critical information became a central issue that affected the findings reported here.

Information Sources

This research effort relied mainly on the collection and analysis of information provided by other sources. For example, we did not attempt to design conceptual airplanes for the Navy's Type A and B missions. The principal sources of information included:

- o Previous V/STOL technology assessments
- o Journal articles and company reports about V/STOL airplane research programs
- o Briefings from aircraft and engine companies currently interested in V/STOL airplane research and development
- o Responses to requests for information sent to companies that develop airframes, aircraft engines, and aircraft transmissions

Specific information was requested about performance, schedule, and cost parameters from past aircraft research, development, and production programs. Because almost all V/STOL airplane programs have been limited to the research phase, the requests included some similar parameters for CTOL airplane programs and helicopter programs.

Products of the Research

Wherever the relevance, quantity, and reliability of the information proved sufficient, analytical estimation techniques were developed. Where lack of information prevented the development of analytical techniques, the reasons for such information gaps were explored and guidelines were formed for dealing with them.

The research has identified the following information gaps that could have a strong bearing on the acquisition decisionmaking process:

- o Until the detailed design and fabrication of a full-scale flight article^{*} are complete, the weight of the airframe and propulsion subsystem cannot be confidently known.
- o Configuration-specific flight-test information is needed to meaningfully estimate a particular V/STOL airplane's performance capability.
- o The number of research and development cycles needed to mature a V/STOL airplane to its performance potential cannot be predicted with confidence.

The research has also developed techniques that will help analysts evaluate the following cost elements for new V/STOL airplanes:

- o Developing an airframe prototype
- o Manufacturing an airframe that has many parts fabricated from composite materials
- o Developing and producing turboshaft/turbojet/turbofan engines
- o Producing aircraft transmissions

In addition, the research has developed techniques that will help analysts judge the extent to which technology must advance to provide specific:

- o Airframe weight reductions through the use of composite materials
- o Lighter weight transmissions
- o Improvements in key design parameters for turbine engines

To use the analytical techniques, one must have certain descriptive inputs for the airplane configuration of interest--inputs that specify, for example, the size of the airframe, engine, and transmission.

^{*} Such a flight article could be a full-scale airplane that is built for the purpose of conducting flight tests.

Other parameters, such as turbine inlet temperature, help characterize the level of technology. None of the parameters, however, directly characterize the airplane's mission performance capability. Although one can use these techniques to evaluate and analyze a cost estimate for an airplane of a particular size and configuration, they will not indicate whether such an airplane could meet a specific set of performance requirements.

The Central Question

At the outset, this research addressed the following question:

When, and at what cost, will configurations that meet Navy performance specifications for V/STOL Type A and B airplanes become available?

Our research shows that a reliable answer to this question can be expected only after the following necessary conditions have been satisfied:

1. Specific configurations have been selected for the Type A and B airplanes;
2. For the selected configurations, full-scale flight articles have demonstrated the flight characteristics required to provide the specified performance;^{*} and
3. For the selected configuration, the weight for the airframe and the propulsion subsystem has been demonstrated through fabrication of a full-scale flight article.

While this research was under way, many aircraft and turbine engine companies were studying conceptual designs for one or more configurations for either, or both, of the Type A and B airplanes. Each configuration was different and the collection of configurations represented a wide range of concepts for achieving vertical takeoff. Each company claimed that advanced technology would make it possible for its configuration(s)

^{*}Such tests are especially important because the unknown problems that accompany the application of new technologies can bias early interest in designs that use technologies about which the least is known.

to meet the performance specifications. Some companies cited extensive laboratory tests to support their claims. Even so, the Navy has not selected any particular configurations (necessary condition 1); moreover, no company has satisfied necessary conditions 2 and 3.

ORGANIZATION OF RAND DOCUMENTATION

Necessary conditions 2 and 3 came from our analysis of V/STOL airplane aerodynamics (Sec. II), structures (Sec. III), propulsion (Sec. IV and V), and the time needed to research and develop V/STOL airplanes (Sec. VI). Setting aside the question of performance, Sec. VI and VII address the questions: How long might it take, and how much might it cost to acquire a mature V/STOL airplane of a particular size?

Because it may be necessary to minimize resource commitments until reasonably confident estimates of performance can be derived from configuration-specific flight tests, Sec. VI examines an R&D strategy intended to minimize the program costs incurred during the early program period when performance uncertainties are greatest. *In contrast to this strategy, the proposed acquisition schedules for Type A and B airplanes have typically called for very large commitments well before any flight tests.*

Each section in this report has a corresponding section in a companion document that gives the details of these analyses.* The companion document also presents appropriate information and analytical techniques that should help in analyzing and evaluating future acquisition programs for V/STOL airplanes.

* J. R. Nelson and J. R. Gebman, with J. L. Birkler, R. H. Hess, P. Konoske-Dey, and W. H. Krase, *Future V/STOL Airplanes: Guidelines and Techniques for Acquisition Program Analysis and Evaluation*, The Rand Corporation, N-1242-PA&E, Privileged Information, October 1979.

II. V/STOL AIRPLANE AERODYNAMICS

A V/STOL airplane's aerodynamic characteristics depend not only on the airframe's shape and size but also on the performance of the propulsion subsystem, the airplane's proximity to the ground, and the flight mode. Aerodynamic phenomena induced by ground proximity and the propulsion subsystem typically have their strongest influence during the vertical flight mode. These factors have a much smaller influence on CTOL airplane aerodynamics because CTOL airplanes only have a horizontal flight mode.* Also, the aerodynamic characteristics at very low horizontal speeds significantly influence the V/STOL airplane's ability to transition between vertical and horizontal flight modes. Because a CTOL airplane cannot become airborne until it has acquired a rather high ground speed, the need to consider low-speed aerodynamics is another factor that distinguishes V/STOL airplane aerodynamics.

Past CTOL airplane acquisition programs have demonstrated that for most flight situations and for most aerodynamic characteristics, wind-tunnel test results provide a reasonably adequate basis for predicting full-scale flight performance for CTOL airplanes. Consequently, engineers can use scale models and wind tunnels to experimentally design and refine the shape for a conventional airplane before a company builds a full-scale flight-test article.

In contrast, past V/STOL airplane research programs and the free world's one V/STOL airplane acquisition effort have repeatedly demonstrated prediction errors when scale model test results have been used to predict V/STOL airplane aerodynamic characteristics. Unfortunately, scale model tests are not nearly as effective experimental design tools for V/STOL airplanes as they are for CTOL airplanes.

Serious prediction problems peculiar to V/STOL airplanes arise in the vertical takeoff mode, transition to wing-borne flight, and

* Horizontal in the sense that the fuselage's longitudinal axis (horizontal reference line) remains approximately aligned with the direction of flight.

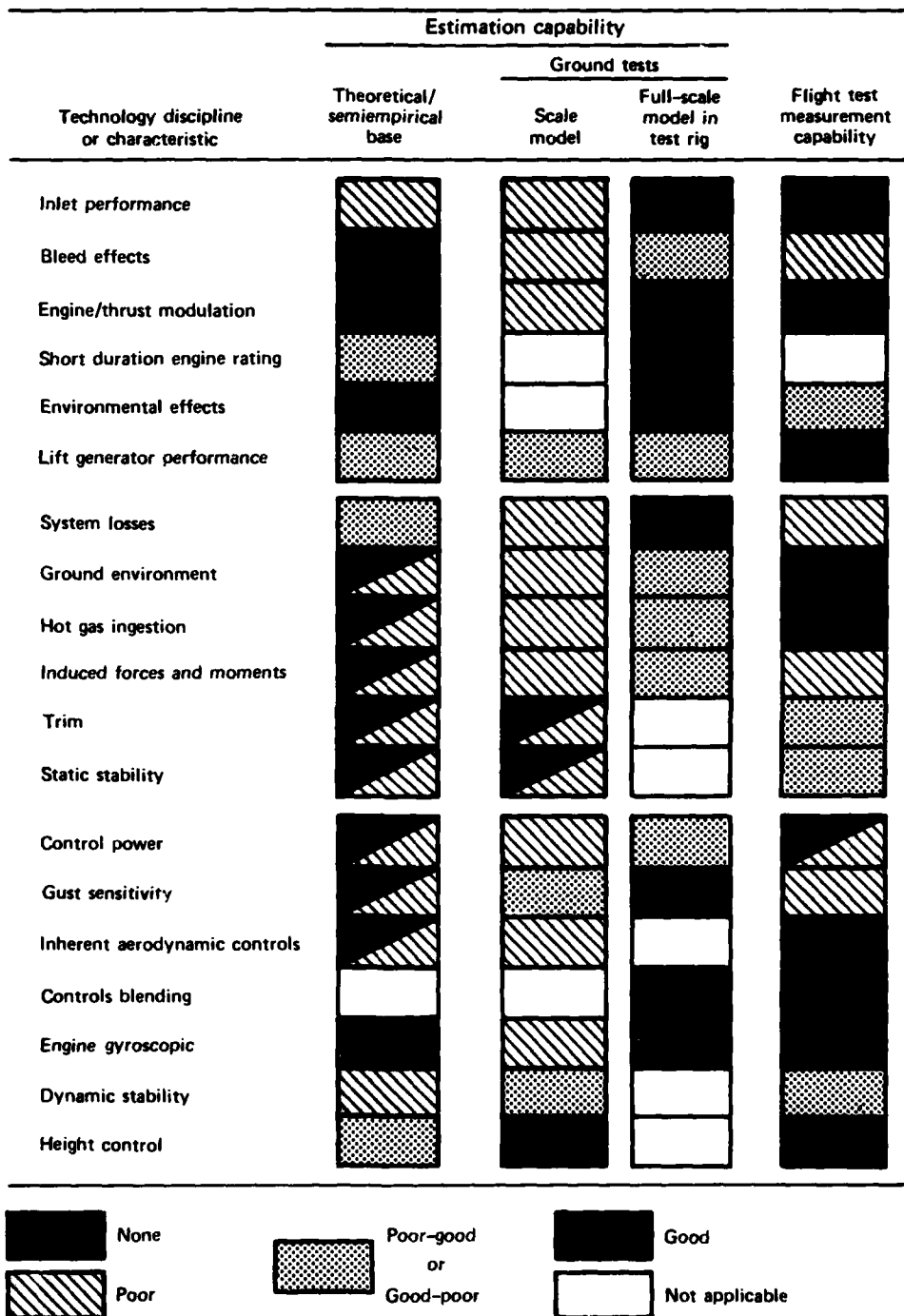
at times even for conventional flight. The prediction problem is especially difficult for the vertical takeoff mode, because the airplane is streamlined for conventional wing-borne flight and thus does not present a streamlined configuration to the vertical flow. Not only does this create a complex vertical downflow, but the ground usually turns some of the downflow back toward the airplane where it further complicates the flow field. This makes it very difficult to estimate, or even model, inlet performance, the forces and moments that the flow imposes on the vehicle, the conditions under which the engine may ingest hot gases, and the extent of ground erosion. Consequently, one cannot expect a reliable estimate for the amount of vertical thrust that the propulsion system must provide for vertical takeoff until full-scale tests have been conducted. Furthermore, one cannot expect a reliable estimate for the performance of the propulsion subsystem until it is thoroughly tested in a full-scale flight-test airplane.

To investigate the adequacy of the existing technology base for designing V/STOL airplanes, the Naval Air Systems Command constituted a special V/STOL Technology Assessment Committee (VTAC). The committee's primary objective was to identify serious gaps in V/STOL-related technologies that could adversely influence the timing and continuity of future Navy developments. The VTAC examined the available methods for estimating and measuring a large number of key design parameters related to aerodynamics. The VTAC considered theoretical/semi-empirical prediction methods, empirical testing procedures using models and full-scale rigs, and flight-test information. Section II of the companion document to this report analyzes the results of the VTAC assessment for each of the classes of V/STOL configurations considered.*

Figure 1 lists the parameters examined by the VTAC and summarizes the VTAC's ratings for jet lift configurations, such as that of the Harrier/AV-8.

The VTAC assigned a rating of good if the estimation/measurement methods could reliably provide results within 10 percent of the actual;

*U.S. Navy V/STOL Technology Assessment, Naval Air Systems Command, unnumbered report, June 1975.



SOURCE: Compiled from VSTOL Technology Assessment, Naval Air Systems Command, June 1975.

Fig. 1 — Aerodynamic estimation and measurement capabilities for jet lift V/STOL airplane configurations

a poor rating meant results could deviate from the actual by 10 to 50 percent; a none rating meant deviations in excess of 50 percent. Each technology discipline listed in the figure summarizes the VTAC's assessment for many important design parameters. Thus, a mixed rating, such as none/poor, means the estimation/measurement capabilities for some parameters rated a "none," whereas other parameters rated a "poor." The purpose of the display in Fig. 1 is to provide an overall sense of the state of the art of aerodynamic estimation and measurement capabilities for a class of V/STOL configurations. Although some of the details vary for some of the other configuration classes (see the companion document), the overall sense portrayed by Fig. 1 appears generally valid. The general sense is that:

- o *There are many important technology areas in which design characteristics cannot be accurately estimated until a full-scale article is either placed in a ground-test rig or flown.*
- o *Even with a full-scale article, there frequently are problems of measuring specific design parameters. Consequently, full-scale articles do not always provide an accurate basis for thoroughly understanding important cause and effect relationships in a specific V/STOL configuration. Thus, design changes should be tested on a full-scale flight article.*

Although the format of Fig. 1 is our own, the technology areas, evaluation categories, and the specific ratings are those used by the VTAC. We generally agree with their overall judgments for the indicated disciplines.

The unpredictable nature of V/STOL airplane aerodynamics makes it difficult to reliably estimate the required size for the propulsion subsystem without having first developed a full-scale flight article. As Sec. VI will show, the multiple development cycles of the Harrier/AV-8 family support this viewpoint. Much of this redevelopment was necessitated by unforeseeable configuration-dependent problems that arose in matching the aerodynamic characteristics of the airframe to the propulsion subsystem.

The preponderance of the evidence indicates that accurate estimates of required propulsion system size and thrust cannot be made without full-scale flight hardware. It seems clear, therefore, that to meet a particular performance level, full-scale flight hardware must be designed, developed, and flown before the size of a V/STOL airplane and the size of its propulsion subsystem can be reliably specified.

III. AIRFRAME STRUCTURE FOR A V/STOL AIRPLANE

Designs for future V/STOL airplanes typically have at least one common feature; they rely on advanced materials to minimize the airframe's weight. Consequently, our research examined the extent to which the Type A and B conceptual designs appear to rely on advanced materials technology. The analysis also examined the benefit that can be expected from postulated improvements in materials. For the conceptual designs examined, it appears that the Type A V/STOL may rely on a 30 to 35 percent reduction in structural weight (compared with current aircraft) due to materials technology improvements, and the Type B airplane may rely on a 20 percent reduction. Such improvements fall outside of at least one aircraft company's assessment of attainable improvement, regardless of cost.*

Moreover, acquisition experience with conventional airplanes raises serious questions about the reliability of pre-full-scale development weight estimates for new airplanes. For example, if a V/STOL airframe proves to have an actual weight that is 12 percent greater than the proposal weight, the total useful load (fuel load plus payload) for Type A conceptual designs could typically be reduced by about 20 percent. Underestimating structural weight prior to the start of full-scale development is not uncommon with CTOL airplanes such as the C-5A, the F-111, the F-14A, and the F-15A.[†] With CTOL airplanes, *unlike vertical takeoff airplanes*, weight overruns can often be compensated for by increasing the length of the takeoff roll. For a vertical takeoff mission with a V/STOL airplane, any weight overrun will decrease either fuel or payload or both.

V/STOL airplanes are more susceptible to weight underestimation than are conventional airplanes because preliminary design weight

*The other companies that supplied information to this research effort did not indicate what they judged to be reasonably attainable improvement.

[†]The pre-full-scale development weight estimate for the free world's only V/STOL airplane to enter full-scale development, the Harrier/AV-8A, was not available.

estimates rely heavily on statistical analysis of conventional airplanes. Although some elementary analysis of the loads transmitted by structural members may augment the statistical analysis, weight estimates are based mostly on correlations derived from the weights and geometries of existing (conventional) aircraft.* Because a V/STOL airframe must accommodate a much more extensive propulsion subsystem than a conventional airplane, more structural inefficiencies will be introduced. Thus, integrating the propulsion subsystem with the airframe will result in a larger weight penalty for a V/STOL airplane than for a conventional airplane. Although some weight allowances are assumed for these effects, the weight estimates for V/STOL airplanes are based largely on the same estimating procedures as for conventional airplanes.

Thus, three different factors may contribute to a tendency to seriously underestimate the weight of a V/STOL airframe. First, recent military CTOL airplane programs have demonstrated a tendency to underestimate airframe weights in general. Second, V/STOL weight estimates are based largely on statistical methods and data for conventional airplanes. Third, the industry's plans for extensive reliance on advanced materials appears overly ambitious according to at least one company's assessment of the attainable benefit from the use of composite materials. Thus, achieving some of the indicated structural weight targets may prove more difficult and more costly than is currently anticipated. Depending on the amount of any weight underestimate, the consequences could range from a modest cost overrun and schedule extension to cancellation of a development program. Moreover, current uncertainties about the durability and electromagnetic characteristics of some composite materials raises further concerns about a strong reliance on composites to achieve large reductions in structural weight.†

*Because of data limitations and the large number of design variables, statistical methods can only provide a rough preliminary estimate of an airframe's weight.

†A. L. Hiebert, *Advanced Composites: Electromagnetic Properties, Vulnerabilities, and Protective Measures*, The Rand Corporation, R-1979-AF, May 1977.

IV. V/STOL AIRPLANE PROPULSION

This section discusses the requirements and design problems peculiar to the development of a V/STOL airplane's propulsion subsystem.* The next section examines the current state of propulsion technology and current trends that may pertain to the propulsion subsystems for future V/STOL airplanes.

DISCUSSION OF REQUIREMENTS

The most evident requirement for the V/STOL airplane's propulsion subsystem is that it must supply a vertical thrust in excess of the vehicle's gross weight, and it must supply this thrust in all kinds of conditions--in temperature extremes, in wind (including cross winds), and with all installation and recirculation effects taken into account. Moreover, the airplane can maintain the proper attitude only if the effective thrust line (including the effects of control jets and other control devices) passes through the center of gravity of the airplane, which may vary depending on the application and loading condition. For this reason, and to permit attitude control about all axes in the presence of disturbances from a number of sources, the propulsion subsystem must also be able to supply effective attitude control moments about all axes.[†] Moreover, the attitude control system must respond much faster than a turbine engine can accelerate.

The process of establishing a formal mission requirement, and hence, the propulsion subsystem requirements, is necessarily interactive. Consideration of the requirements for a V/STOL airplane's propulsion subsystem will have to include:

* Although there have been a number of research and experimental programs, there has never been a full-scale development of an operational article in the United States.

[†] A CTOL airplane uses exclusively aerodynamic control surfaces to maintain attitude control because it does not fly at the low speeds where such surfaces become ineffective.

1. Airplane operations in a salt-spray environment.
2. For the Type A airplane, Marine Corps assault landings at unprepared sites impose a particularly critical requirement on a V/STOL airplane because of possible ground erosion. The recirculation of debris can reduce the pilot's visibility and severely damage the propulsion subsystem. Thus, ground erosion may set a practical upper limit on the disc loading that can be used.* Figure 2 shows that such a limit could severely restrict the propulsion concept alternatives.†
3. For operation from relatively small ships, such as destroyers, the aerodynamic wake of the ship is likely to be highly turbulent and to contain very high and variable velocity gradients. While slowing the ship or changing its angle relative to the wind may alleviate these problems, the requirement to operate in high sea (and wind) states will probably restrict the ship headings that can be used in order to avoid excessive ship roll or heave motions. Moreover, operations in high sea states may subject the V/STOL airplane to large and variable wind gradients that would require the propulsion subsystem to supply large amounts of power to provide exceptionally large control moments.
4. The Type B airplane must have a capability for supersonic flight, which restricts the feasible propulsion concepts to the lift fan and lift jet alternatives. Figure 2 shows that these alternatives typically lead to designs that have very high engine exhaust velocities. Moreover, the temperature of the exhaust gases typically increases with the exhaust velocity. Consequently, the nature of the surface from which the Type B airplane must operate could impose further limitations on both the selection of the propulsion subsystem concept and the design of that subsystem.

*The disc loading is the thrust provided by a thruster, divided by the area swept by that thruster.

†The Harrier/AV-8, with a turbofan engine, falls in the lift jet class in Fig. 2.

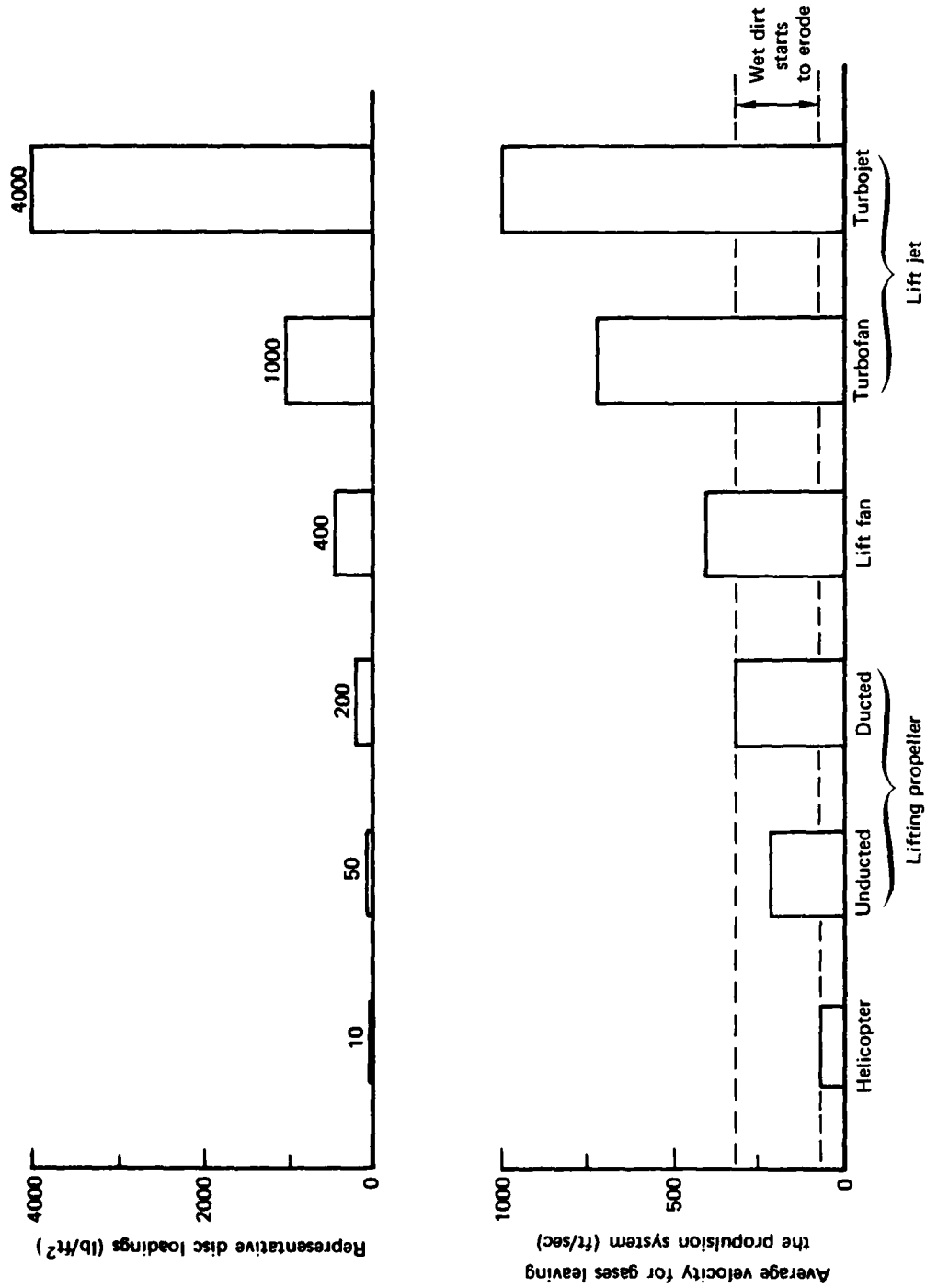


Fig. 2 — Influence of propulsion concept on potential surface erosion problems

In addition to these minimum requirements, it frequently is assumed that a multi-engine V/STOL airplane must be able to operate safely with one failed engine. To maintain control of the airplane, the remaining power must be distributed (e.g., by cross-shafting) to all of the thrust producers (fans, rotors, etc.). However, even V/STOL airplanes that can land with a failed engine still have many potentially fatal failure modes. For example, almost all multiple thrust producer configurations are vulnerable to a failure of one thruster, or in some cases to a failure of a transmission. Thus, the complications and design penalties introduced by cross-shafting or cross-ducting are many and they do not result in a completely fail-safe propulsion subsystem.

Because the criterion for safe operation with one engine failed is insufficient to assure a fail-safe propulsion subsystem, and because the criterion greatly complicates the propulsion subsystem, it may be worth reconsidering whether a single-engine-out criterion is really necessary for Type A and B V/STOL airplanes that have multiple engines. The continuing acquisition of single-engine airplanes such as the AV-8A, the A-7, and the F-16 demonstrates a continuing willingness to operate airplanes that do not have a one-engine-out capability. Requiring more than this from a V/STOL airplane increases complexity, weight, and cost and still does not provide a fail-safe propulsion subsystem.

DESIGN PROBLEMS PECULIAR TO V/STOL AIRPLANES

The installation of a turbine engine in a V/STOL airplane can have a major effect on its performance. To obtain good inlet pressure recovery and flow distribution at near-zero flight speeds requires a bell-mouth type of inlet having large lip radii of curvature--a feature that cannot be accepted from the standpoint of high-speed drag. Moreover, inlet flow maldistribution due to large angles of attack can be quite serious, resulting in substantial thrust losses, as well as changes in resultant thrust line. Although various palliative solutions have been developed, each configuration will have its own set of problems, requiring experimentally verified solutions.

In general, the design and development of a propulsion subsystem for a V/STOL airplane is much more demanding than the design and development of a propulsion subsystem for a CTOL airplane.

- o The stringent requirements on the thrust level, thrust line, and control system response times are unique to V/STOL airplanes.
- o Because of the wide disparity between the thrust required for takeoff and that required for subsonic cruise, it is difficult to design for adequate power during takeoff and transition, and at the same time achieve efficient operation during cruise.
- o A requirement for vertical landing, even with an engine failure, complicates the V/STOL propulsion subsystem.
- o The V/STOL propulsion subsystem not only contains more mechanical components than a CTOL propulsion subsystem, but it is difficult to estimate the weights for these components because of a lack of data on similar configurations.
- o Even though the propulsion subsystem for a V/STOL airplane is more complex than that for a CTOL airplane, the V/STOL propulsion subsystem must be more reliable and maintainable. Otherwise, the cost of supporting dispersed operations could become prohibitive. Low reliability could be disastrous for a V/STOL airplane if the principal rationale for such an airplane is to reduce force vulnerability by dispersing the aviation forces.
- o For V/STOL airplanes, the designer must choose from a wide range of fundamentally different propulsion concepts, whereas for CTOL airplanes, the range of alternatives is much smaller and most of them have matured through repeated application to operational airplanes.

All of these factors contribute to the complexity and uncertainty associated with estimating V/STOL propulsion system performance.

V. TRENDS IN PROPULSION TECHNOLOGY

Aircraft and turbine engine companies that have studied the Navy's performance specifications for Type A and B airplanes indicate that such airplanes would have to employ significant advances in propulsion technology, especially turbine engine technology. To understand the extent of the advances being considered, this section examines the current state of propulsion technology and trends that may affect future V/STOL airplanes.

The information acquired during this research pertained mostly to turbine engines that power operational aircraft, and to a lesser extent, transmissions used in operational aircraft. In both cases, some material was available from helicopter and CTOL airplane acquisition programs. There is also, of course, the experience of the turbofan engine that powers the Harrier/AV-8A. Much of this information can be used to analyze and evaluate future V/STOL airplane acquisition programs. Because little useful data could be found for other propulsion subsystem components peculiar to V/STOL airplanes, this section focuses on turbine engines and transmissions.

TURBINE ENGINE TECHNOLOGY

The Harrier/AV-8A Experience

The Pegasus engine is the only turbine engine to power an operational V/STOL airplane in the free world. That engine, along with the Harrier/AV-8A airplane that it powers, provides the only source of operationally proven information for a V/STOL airplane propulsion subsystem.

Figure 3 illustrates the evolution of both the Pegasus engine and the Harrier/AV-8A. Over the years, the Pegasus' designers have incorporated advances in turbine engine technology to increase the turbine inlet temperature. This has helped increase the amount of thrust that the Pegasus provides for each pound of engine weight.

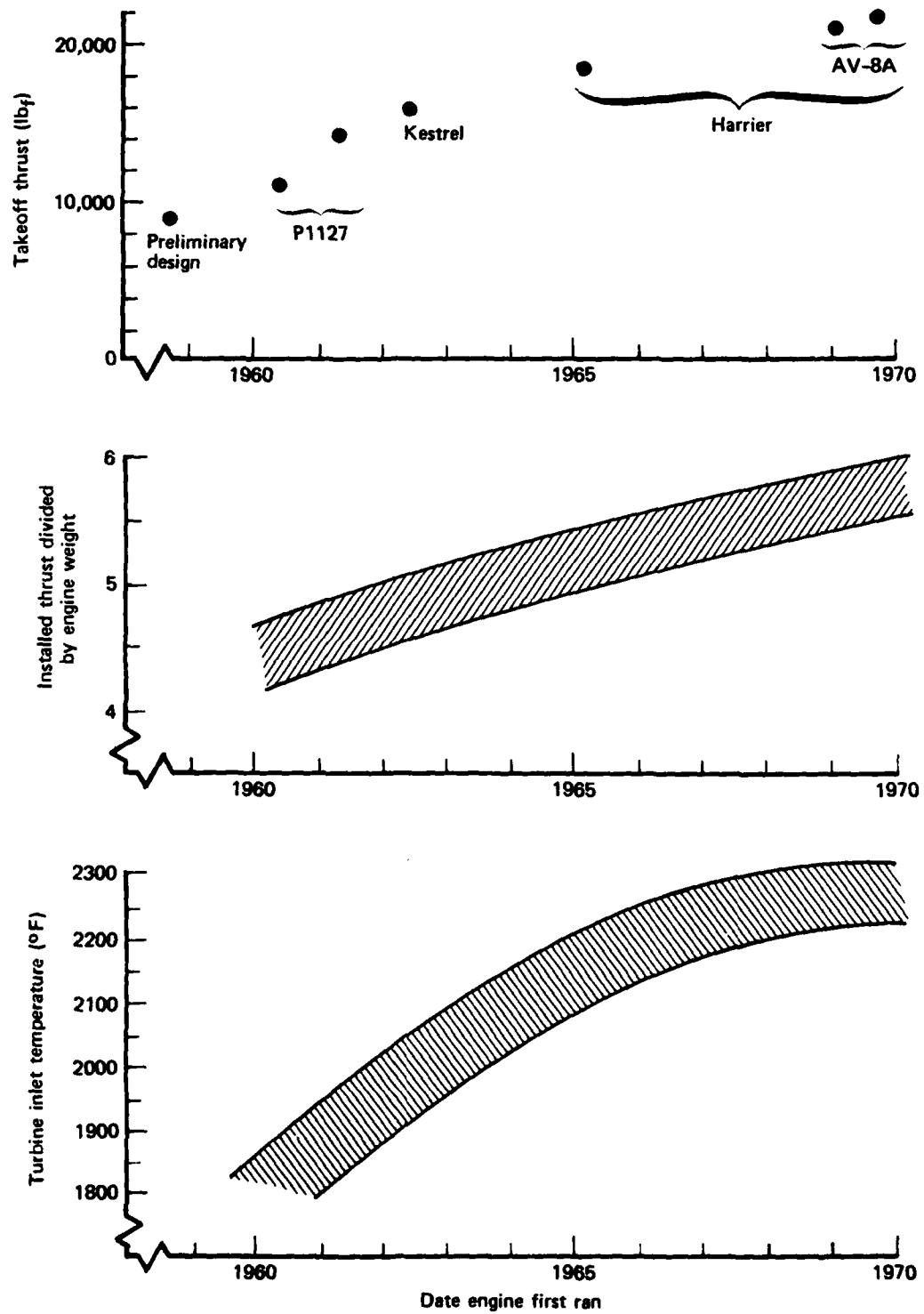


Fig. 3 — Evolution of the Pegasus family of engines

CTOL Airplane And Helicopter Experience

Analysis of the development histories for military jet engines (turbojet and turbofan) has shown that designers have generally tended to use advancing technology to increase the turbine inlet temperature.* The present analysis has extended that previous research to develop a single method for analyzing the trends of both shaft engines (used in turboprop and helicopter applications) and jet engines. The data and methods allow one to compare certain technical characteristics for a proposed turbine engine with historical trends. This may be done by using a single parameter: for instance, turbine inlet temperature or thrust-to-weight ratio. Alternatively, it may be done by using several parameters simultaneously: specific fuel consumption, a total pressure term (engine pressure ratio times the maximum dynamic pressure for the flight envelope), maximum thrust, engine weight, and turbine inlet temperature. In either case, if it is assumed that historical trends will continue into the future, extrapolation can be used to estimate when some specified level of engine performance could become available. Because there is no assurance that the trends will continue indefinitely into the future, the main value of trend analysis is to help identify overly optimistic expectations.

For example, if a proposed V/STOL airplane program relies on a future engine that is to operate at a turbine inlet temperature well above the extrapolation of the historical trend, this would suggest above average program risk. Similarly, if the date at which the engine is to pass its Model Qualification Test, as estimated by trend extrapolation, exceeds the date at which the proposed V/STOL program requires an engine to have passed its Model Qualification Test, then this, too, suggests an above average chance that the program will fail to satisfy its performance, schedule, and cost goals.†

* See Sec. V of N-1242-PA&E and J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

† Although such a trend analysis can identify cause for concern, it cannot assure that a particular engine development effort will necessarily meet with success.

Turbine engine and aircraft companies that have studied the Navy's performance specifications for Type A and B airplanes indicate that the propulsion subsystems for such airplanes will probably need engines with turbine inlet temperatures in the range of 2800 to 3200 F. *Extrapolation of the historical trend shows that such temperatures fall above the extrapolated trend line for the 1980s.*^{*}

AIRCRAFT TRANSMISSION TECHNOLOGY

For some V/STOL airplane configurations, the weight of mechanical transmissions can represent a large portion of the propulsion subsystem weight. Aircraft companies that have studied the Navy's performance specifications for Type A and B airplanes indicate that mechanical transmissions for such airplanes would have to employ advances in technology to produce sufficiently lightweight transmissions. To help assess the extent of such advances, our research has developed a method that compares the critical design parameters for past transmissions with like parameters for any proposed transmission. To apply the method to a proposed transmission, it is necessary to know the transmission's design power level, output shaft speed, output torque, and estimated weight.[†]

Some companies have studied V/STOL airplane configurations that would use transmissions with design power levels that are high compared to currently operational transmissions, but other details (output torque, etc.) were not available.

PROPULSION SUBSYSTEM RELIABILITY

High thrust, high reliability, low specific fuel consumption, and low weight are all crucial design goals for the propulsion subsystem that powers a V/STOL airplane. Although historical trends for turbine inlet temperature and thrust-to-weight ratio suggest further increases for both of these parameters, such increases may come at the expense

^{*} See Fig. 16 in Sec. V of N-1242-PA&E.

[†] See Figs. 24 through 27 in Sec. V of N-1242-PA&E.

of some other design goal (e.g., reliability).^{*} Unfortunately, we are ill-equipped to understand the tradeoffs between performance and reliability without first building and flying full-scale hardware.[†] Thus, although trends suggest that further advances may be forthcoming, the consequences are not well understood and will require full-scale hardware tests before it will be known whether following historical trends will yield an acceptable propulsion subsystem for the peculiarly stringent requirements of a V/STOL airplane.

^{*}For example, the engine designers for commercial transport airplanes appear to trade lower turbine inlet temperature for higher operational reliability.

[†]The advantage of demonstrating and testing the entire V/STOL propulsion subsystem prior to high-volume production commitment is illustrated by a brief review of past and current propulsion subsystem problems for conventional aircraft: (1) the influence that the cyclic variation of the throttle has had on engine component life for the engines that power the F-14A, (2) the abortive attempt to use a new material for the RB-211 engine that led to serious schedule and cost overruns, and (3) the reliability problems that the F100 engine is still having five years after passing its Model Qualification Test. (See Sec. V of N-1242-PA&E for details.)

VI. TIME NEEDED TO DEVELOP A V/STOL AIRPLANE

The development schedules proposed for both V/STOL Type A and Type B airplanes present overly optimistic views of the time needed to develop an operational V/STOL airplane. The schedules, moreover, reflect a development strategy that would likely consume more time than an alternative strategy that realistically recognizes the nontrivial uncertainties peculiar to the development of V/STOL airplanes. This section presents the basis for these statements by analyzing past V/STOL programs and outlining an alternative development strategy. This section also examines the time required to develop the propulsion subsystem, which appears to be a pacing item in a V/STOL development program.

RATIONALE FOR AN ALTERNATIVE DEVELOPMENT STRATEGY

Given a set of minimum performance requirements for an airplane, designers can determine the minimum necessary size for the airplane and the propulsion subsystem only if they have reliable information about the flight characteristics for the general arrangement of the airframe and the propulsion subsystem. For a V/STOL airplane, full-scale flight tests provide the only reliable source of information for the relevant flight characteristics. Thus, before the V/STOL airplane designer can confidently establish the minimum necessary size for the operational airplane, he must have flight-test results for a V/STOL airplane that has the same general arrangement of the airframe and the propulsion subsystem.

The development schedules typically contemplated for V/STOL Type A and B airplanes emphasize large early investments on production prototypes that would receive minimal design changes after the first flight. Even though the contemplated schedules call for a prototype phase, the prototype in actuality would be a nearly fully developed article to which the aircraft companies expect only minimal changes prior to starting full-scale production. Several schedules allow only 3.5 years between the first flight of the prototype and the start of

production. The preponderance of the evidence^{*} suggests, however, that one should expect several design iterations before the vehicle size and the propulsion subsystem size are finally established.

The typically proposed schedules for V/STOL Type A and B airplanes could be improved by adding an austere initial stage that would rapidly proceed to first flight and thereby provide an early opportunity to reformulate the design point and crucial configuration details. Depending upon the extent of concept reformulation, it may prove beneficial to proceed with a second austere pass, again quickly proceeding to first flight. Conventional full-scale development would start only after suitable flight characteristics have been demonstrated. Past experience suggests that the rapid acquisition of information about the flight characteristics for a specific configuration and the early reformulation of the design point and configuration details could be a crucial factor in the timely development of an operationally suitable V/STOL airplane.

V/STOL AIRPLANE RESEARCH AND DEVELOPMENT EXPERIENCE

Past V/STOL programs have repeatedly demonstrated that austere experimental programs can acquire information that is crucial to estimating subsystem performance for V/STOL airplanes. Such programs have been accomplished at a fraction of the time and cost that would have been needed by a full-scale development program that developed an engine and airframe optimized for a specific mission. If one accepts the thesis that V/STOL airplane development probably involves one or more iterations, one would like to minimize the time and cost of the first iteration without adversely influencing subsequent iterations. Incremental development is one approach to achieving early results at relatively low cost. Noteworthy examples are provided by the XfV-12A program and the P1127 family of airplanes that yielded the Harrier/AV-8.

The experience of other V/STOL programs also supports the desirability of an incremental approach. For example, by using components

^{*} See Sec. II and IV regarding the difficulties encountered in estimating V/STOL airplane aerodynamics and propulsion-induced effects. Also see the subsequent subsections on V/STOL airplane research and development experience.

from existing engines and airframes, many experimental/research programs have accomplished a first flight within two or three years from contract go-ahead. Of the two dozen V/STOL programs examined, three-fourths accomplished first flight in less than three years, and nearly one-third accomplished first flight in less than two years.

The XFV-12A Program

The XFV-12A program, like many other V/STOL programs, has used extensive portions of existing airplanes to quickly test a V/STOL propulsion concept. For the XFV-12A, the nose gear, forward fuselage, and main landing gear came from the A-4; the inlet and the wing box came from the F-4. The XFV-12A is a technology prototype program sponsored by the U.S. Navy to investigate the potential applications of the thrust augmentation concept for a fighter/attack V/STOL airplane. The program started in 1972, and has had an initial series of tethered tests which showed that the augmenters would have to be improved. The contractor was incorporating such improvements when funding for FY 1979 was deferred.

Although the XFV-12A has not made a first flight, the research program has provided valuable information about the performance of the original design for the thrust augmentation scheme. Moreover, the design changes proposed by the contractor involve changes to the thrust augmenters and not to the airframe structure or the turbine engine powering the propulsion subsystem. The contractor recognizes that it is crucial to improve the performance of the augmenters and to demonstrate the practicality of this type of propulsion configuration.

If the Navy had entered a full-scale development program in which a modern airframe and engine were specifically developed for the XFV-12A configuration, much more than the 80 million dollars already invested would probably have been spent prior to achieving the current performance assessment for the initial design of the thrust augmenters. Although the contractor believes that design modification will yield a suitably efficient thrust augmenters, it does not appear prudent to embark on a full-scale development program until after such an improved augmenters has been flight demonstrated in a full-scale vehicle.

Evolution of the P1127 Family of V/STOL Airplanes

The Marine Corps has wanted to receive its first 77 AV-8B airplanes during 1984 and 1985, nearly thirty years after European engineers formulated the general arrangement and rough dimensions for that airplane.* During this nearly thirty-year period, the configuration has evolved through four distinct generations (see Fig. 4). As each generation started, the developers thought that they would produce an operationally satisfactory configuration for a fighter/attack mission that required a vertical takeoff and a vertical landing.

The first generation (designated the P1127) yielded two flight vehicles that demonstrated the flight concept for the general arrangement of the engine and the airframe. To take off vertically, however, the aircraft could carry no payload and only a three-minute supply of fuel. The second generation (designated the Kestrel) yielded nine flight vehicles that had a higher thrust engine and significantly modified aerodynamic details. The third generation (designated the Harrier) saw even higher thrust models of the engine, larger inlets, additional aerodynamic refinements, and a completely redesigned structure--with the same general arrangement as the P1127. Both the Royal Air Force and the U.S. Marine Corps have deployed models from this third generation. To carry a meaningful payload, however, even the latest model procured by the Marine Corps (designated the AV-8A) often uses a short takeoff roll. The fourth generation (AV-8B) would increase the payload for both vertical and short takeoff. This generation would have a slightly larger wing that would use a supercritical airfoil, new flaps, and major structural components fabricated from composite materials. It would also have a slightly higher thrust engine and aerodynamic refinements that improve the vertical takeoff performance.

In view of the problems in predicting V/STOL airplane aerodynamics and the stringent requirements imposed on a V/STOL airplane's propulsion subsystem, one cannot dismiss the multi-cycle development experience of the P1127 family of airplanes (see Fig. 4). Major

* Concept formulation for the P1127 traces back to 1954.

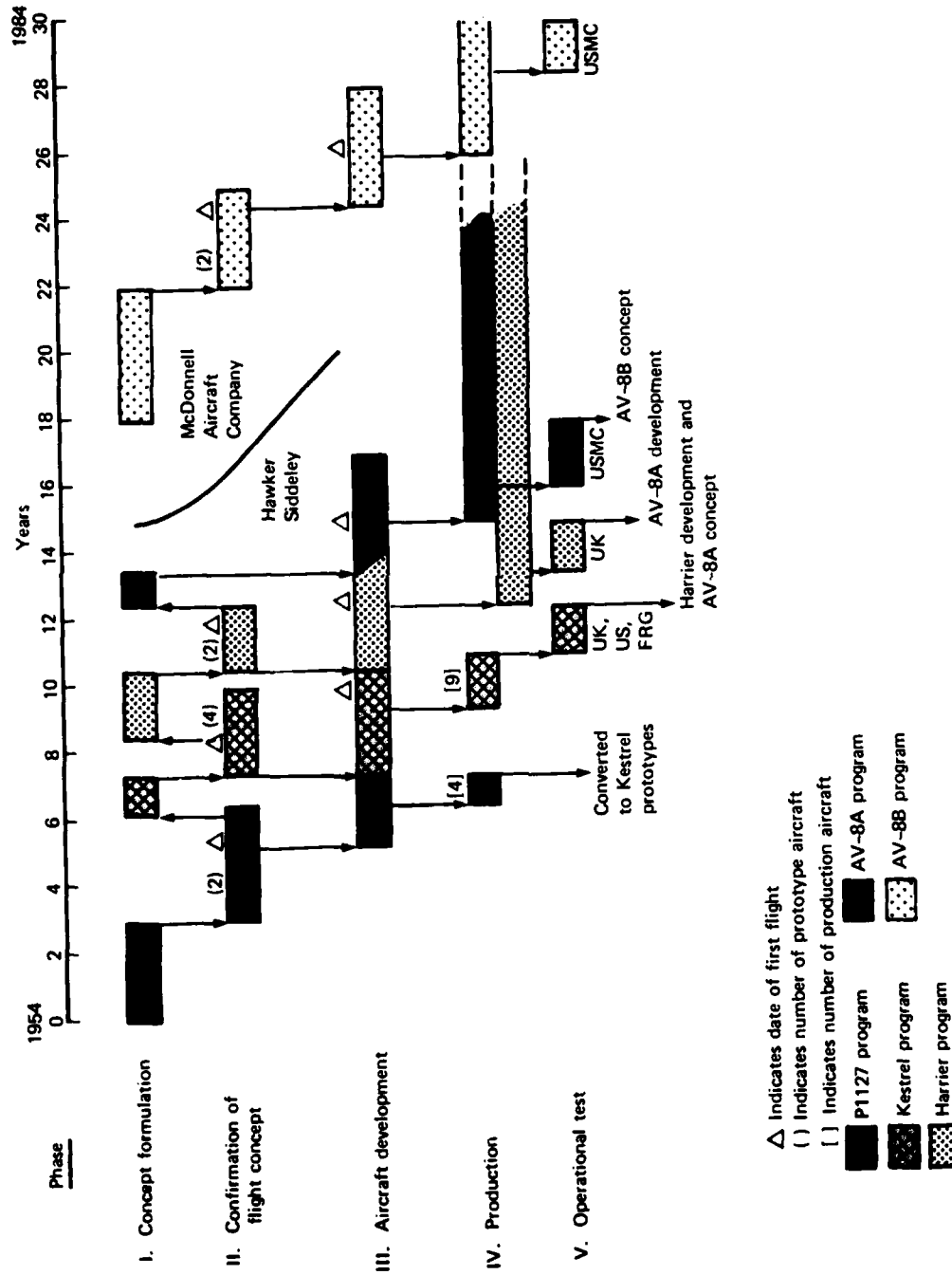


Fig. 4 — Development cycles preceding the planned operational test of the AV-8B

SOURCE: Compiled from Tables 25 through 29 in N-1242-PA&E.

reformulation of the airplane's design point (e.g., vertical takeoff weight and engine size) occurred in going from the P1127 configuration to the Kestrel configuration, and again in going to the Harrier configuration. The Harrier was an almost completely redesigned airplane in terms of design details, although very similar to the Kestrel and the P1127 in overall shape, propulsion system concept, and general arrangement. A rather minor change in the configuration occurred in going from the Harrier to the AV-8A; however, a very significant change in the shape and construction of the wing is taking place in transition from the AV-8A to the AV-8B configuration. Thus, *three major changes in the design point have occurred in the evolution of the P1127 family.* These major reformulations of the design point took place notwithstanding the fact that as each program started development, the designers thought that the resulting flight article would be an operationally useful vehicle in the vertical takeoff mode.

A counter argument to the lesson drawn from the P1127 experience is that each of the programs leading up to the AV-8B was conducted with a very austere set of resources. One might argue, therefore, that some of the difficulties encountered might have been caused by underfunding of the effort, rather than an inability to accurately anticipate the performance characteristics of the proposed configuration. However, there are many important areas of V/STOL airplane design that require a full-scale flight article to accurately estimate a configuration's flight characteristics (difficulties with the XFV-12A are a recent remainder of this fact). Thus, although additional funding undoubtedly would have speeded up the evolution of the Harrier/AV-8, there are many areas where additional design work and analysis simply cannot substitute for the information obtained from experimentation with full-scale flight articles.

The austere multiple-cycle development that characterizes the evolution of the P1127 family may offer a reasonable model for future V/STOL airplane development. With benefit of hindsight, we can now associate specific development objectives with each generation through which the P1127 family has evolved. For example, to the P1127 development we can associate the objective: (1) *determine the general flight*

characteristics; to the Kestrel development we can associate the objective: (2) *determine the general operational characteristics*; to the Harrier/AV-8A: (3) *develop a specific operational configuration*; and finally, to the AV-8B: (4) *enhance configuration performance*.

A multiple-cycle austere development has some obvious shortcomings; for the P1127 family, it will have taken thirty years from the initial concept to the deployment of combat-ready equipment that has a useful mission capability following a vertical takeoff. Obviously, one would not want to execute each of the development steps exactly according to the P1127 history. It may, however, prove useful to consider the sequential development objectives associated with the evolution of the P1127 family of airplanes.

For example, the typically contemplated development schedules for V/STOL Type A and B airplanes require that the first three objectives be accomplished simultaneously--with no prior flight-test experience. At a minimum, it would seem, full-scale development of a specific operational configuration should not begin until flight tests have been used to determine the general flight characteristics.

TIME TO DEVELOP THE PROPULSION SUBSYSTEM

The calendar time required to develop and test a new turbine engine has increased as engines incorporate technology advances to increase the values for technical parameters, such as the thrust-to-weight ratio. For example, the amount of development testing that an engine receives before it passes the Model Qualification Test has significantly increased during the past three decades. Moreover, additional endurance and service tests have recently been promulgated for all military turbine engines. Even before these tests occur, a V/STOL airplane's propulsion subsystem must undergo an Integrated Propulsion System Test. Altogether, one can now expect 10 ± 2 years to elapse from the time full-scale development starts on the engine to the time that such an engine completes the Accelerated Service Tests that indicate the engine's reliability and maintainability. Of course, it could take more time if major design problems arise or if the original design thrust level is changed *by more than only a few percent*.

For mechanical transmissions, depending on the design power level and the output shaft speed, full-scale development of a new transmission for a V/STOL airplane will probably require at least 2.5 to 5 years, with the first third of the time allocated primarily to design and the latter two-thirds to a combination of testing and redesign. To this time, an additional 3 to 6 years should be added for Integrated Propulsion System Tests, Simulated Mission Endurance Test, and the Accelerated Service Test.

Because the power and speed capabilities actually demonstrated by a given transmission sometimes fall short of the designer's expectations, it may be prudent to develop a technology demonstrator before the design points are set for either the transmission or the engine. Redesigning the engine to match the capability of the transmission can prove not only costly but time consuming, as was demonstrated by the T-700 prototype engine program.*

Although it can take a decade or more to develop and demonstrate the service suitability (e.g., as indicated by the Accelerated Service Test) of a propulsion subsystem for a V/STOL airplane, a new turbine engine for an experimental airplane can qualify for flight tests by passing the Preliminary Flight Rating Test. New engines often pass this test within 3 to 4 years from the start of full-scale engine development. Thus, a new engine can be made available for experimental flight tests very early in the research and development process.†

TIME TO DEVELOP A V/STOL AIRPLANE

Depending upon the V/STOL airplane concept, the specific configuration of the airframe and propulsion subsystem proposed, and the selected research and development strategy, it can take from 2 to 6 years to develop an article for flight test. Thus, the designer can expect that it will take at least 4 ± 2 years to begin to obtain reliable information about the flight characteristics for the proposed configuration. Based on previous V/STOL research experience, significant

* See Sec. VI of N-1242-PA&E.

† The engine would have to be resized once the airplane's flight characteristics have been determined.

modifications to the detailed design of the airframe and/or propulsion subsystem will probably require another flight article and further flight tests to determine the revised flight characteristics. Thus, it appears reasonable that, with two iterations, it will take 7 ± 2 years to reliably determine the flight characteristics for the selected general arrangement of the airframe and the propulsion subsystem. It could take even longer, of course, if the design details of the revised configuration are again revised. In that case, an additional flight article and further flight tests will be needed.

Once the flight characteristics, including propulsion-induced effects, are reliably known, the designer can establish the minimum necessary size for the airplane and its propulsion subsystem. At that point he can establish the probable sizes for the propulsion subsystem components. Assuming that the turbine engine designers have already passed a Preliminary Flight Rating Test for an engine similar but of different size to the one required, it might only take 8 ± 2 years of additional effort to proceed through the Accelerated Service Test. Thus, for a V/STOL airplane configuration that uses a previously untried general arrangement of the airframe and the propulsion subsystem, one can expect 15 ± 4 years to elapse from the start of the program to the completion of the Accelerated Service Test. If the reliability demonstrated by the test is no better than that which conventional combat airplanes have demonstrated early in their operational life, one can expect perhaps an additional 5 years to elapse before the reliability of the propulsion subsystem is consistent with the requirement to operate the proposed V/STOL airplane from a remote location with minimal support resources. Because of the heavy emphasis on propulsion subsystem performance, one can expect that the tradeoffs between performance and reliability may gravitate more towards performance than reliability. Even if reliability does not prove to be a problem, one can still expect 15 ± 4 years to elapse from the start of a new V/STOL airplane program to the completion of the Accelerated Service Test and the deployment of operational V/STOL airplane units to forward operating locations with sparse support resources.

VII. FUNDS NEEDED TO DEVELOP A V/STOL AIRPLANE

ANALYTICAL TECHNIQUES

To supplement methods for estimating airframe R&D costs, cost information has been acquired for experimental and prototype airframe R&D programs.* For turbine engines, previous methods for estimating turbine engine R&D costs were extended by adding shaft engines to the jet engines (turbojet and turbofan) previously considered. Because building test hardware accounts for about one-half the turbine engine development costs, test engines are now included. Because the extent of the technical advancement sought by a turbine engine R&D program can significantly influence the program's cost (note, for example, the 250 percent cost increase experienced by the RB 211 program), this research attempted to measure the amount of advance sought by a program and to relate that advance to the expected R&D costs.

V/STOL airplanes may use more advanced materials that are more expensive than materials usually used to fabricate airframes. Thus, Sec. VII of N-1242-PA&E presents an approach and data for making rough estimates of the potential range of costs to manufacture finished parts for the airframe structure.

OBSERVATIONS ABOUT THE COST TO ACQUIRE A NEW V/STOL AIRPLANE

Research and Development Cost

The airframe R&D cost for an experimental program (e.g., the XFV-12A) typically amounts to a small fraction of the full-scale development costs for similar vehicles. For example, the airframe R&D cost for a full-scale development program can amount to 5 to 15 times the cost of an experimental or prototype program for conventional airplanes. (A V/STOL airplane may even exceed this range.)

To research and develop a new turbine engine for a V/STOL airplane, the R&D cost would probably range between several hundred million

* Section VII of N-1242-PA&E documents the cost information and estimating relationships from this research effort.

dollars and a billion dollars, depending on the type of engine. It appears that the cost to research and develop a transmission could fall in the range of \$30 to \$100 million if the transmission must significantly reduce speed while transmitting a large amount of power.

Although other components of the propulsion subsystem, such as fans and drive shafts, can contribute significantly to development and procurement costs, data were not available for such components.

Procurement Cost

The cost to procure an airframe structure that has 70 percent of its parts (by weight) manufactured from graphite-epoxy will probably cost from 1 to 2 times as much as an all-aluminum structure of equal weight. The principal uncertainties pertain to the cost of the graphite-epoxy material and the cost to manufacture airframe parts. However, even if the 70 percent graphite-epoxy structure cost twice as much, this factor alone would probably increase the total recurring cost to produce the airframe by only about 20 percent.*

The cost to procure turbine engines for a V/STOL airplane will be more than that for a comparable size CTOL airplane powered by a similar engine type because a V/STOL airplane requires more installed thrust/power than a CTOL airplane. If the V/STOL airplane requires an engine(s) that has 2 to 4 times as much thrust/power as the engine(s) in the comparable size CTOL airplane, then the analytic models developed by this research suggest that the engine(s) powering the V/STOL airplane will cost 2 to 3 times as much to procure as the engine(s) that powers the CTOL airplane.

Although the drive system for a vertical takeoff aircraft, such as the CH-47D helicopter, can cost on the order of several hundred thousand dollars per aircraft, drive systems for comparable size V/STOL airplanes may not cost that much because they would generally have drive systems designed for less reduction in speed and a lower output torque. However, the total power transmitted to a V/STOL airplane's transmission may well exceed that of existing flight-demonstrated

*The value of using composites in lieu of conventional metals depends on the airframe weight reduction that can be attributed to the composites.

transmissions. Unfortunately, the limited data available does not allow us to discern the relative extent to which power (higher for the V/STOL airplane), torque (higher for the CH-47D helicopter), and reduction ratio (higher for the CH-47D helicopter) influence manufacturing cost.

IMPLICATIONS FOR THE DEFENSE SYSTEM ACQUISITION REVIEW PROCESS

Before the Defense System Acquisition Review Council can expect a reasonably reliable estimate of the cost to acquire a V/STOL airplane that meets a specified set of performance requirements, *the military service proposing a weapon system acquisition program based on a particular V/STOL airplane configuration will first have to flight demonstrate that configuration.* The proposing service could accomplish this, within existing procedures, by conducting an experimental research program, such as the XFV-12A, prior to proposing the acquisition of a specific weapon system.